Solid particle number emissions from heavy-duty diesel vehicles under real-world driving conditions and standard testing cycles

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Introduction

The concern of vehicle exhaust particles affecting human health and the limitations of the traditional mass based particulate matter regulation method have driven the development of particle number based regulation method in Europe by the Particle Measurement Program (PMP). The PMP measures solid particles larger than 23 nm, where solid particles are operationally defined as particles that can survive after a volatile particle remover. The PMP protocol has been intensively tested under laboratory conditions over standard driving cycles [1]. However, there are concerns as to whether laboratory testing cycles represent the real-world driving conditions, especially for the newly regulated solid particle number emissions. It has been found that artifact particles can be formed downstream the PMP system by re-nucleation of semi-volatiles, while another commonly used volatile particle remover, the Catalytic Stripper (CS) shows much less tendency of forming artifact particles [2].

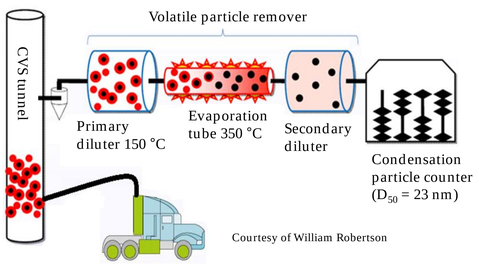
Objectives

- Compare particle number and particle mass emissions during on-road driving conditions and a standard driving cycle;
- Evaluate the PMP methodology of removing volatile particles over real-world driving conditions;
- Compare particle number emissions below the PMP and CS, with an emphasis on the formation sub 23 nm particles.

Methods

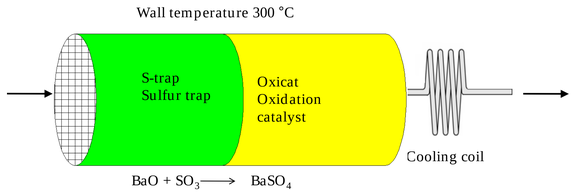
Experiments were carried out using the University of California Riverside, College of Engineering – Center for Environmental Research and Technology (UCR CE-CERT)'s Mobile Emission Laboratory (MEL) under real-world driving condition and a standard testing cycle, the Urban Dynamometer Driving Schedule (UDDS).

Particle Measurement Program (PMP) system schematic



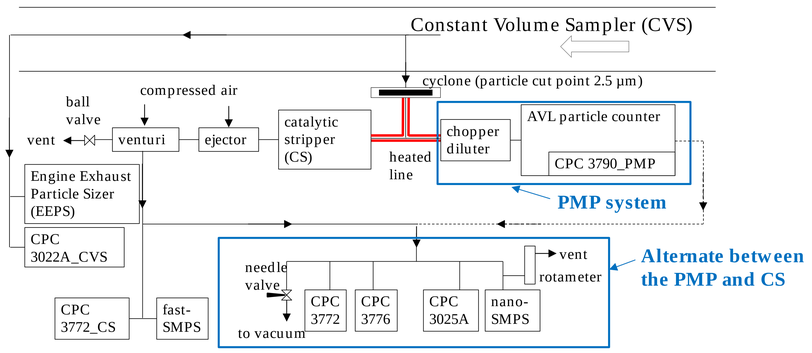
The PMP system used in this study was an AVL particle counter. It consists of a primary chopper diluter heated to 150 °C, an evaporation tube heated to 350 °C, a perforated tube as the secondary diluter, and a TSI 3790 CPC with a cut point of 23 nm.

Catalytic Stripper (CS) schematic



The Catalytic Stripper (CS) consists of two traps, S-trap and Oxicat. The S-trap removes SO_3 by reaction shown above and the Oxicat has an oxidation catalyst to help oxidize hydrocarbon compounds [3].

Schematic of setup



Vehicle parameters

Vehicle	Freightliner class 8
Engine	2000 Caterpillar C-15 (14.6L)
Fuel	CARB ULSD (sulfur: 8 ppmw)
Lube oil	SAE 15W-40 (sulfur: 0.29%)
Diesel particulate filter (DPF)	Johnson Matthey Continuously Regenerating Trap (CRT™)
Vehicle weight	65,000 lb
Miles	41442 miles

CPC cut-off diameters

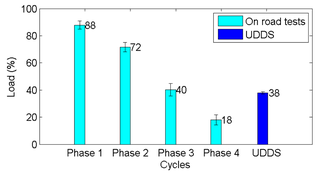
CPC model	D_{50} (nm)	Sample location
3022A_CVS	7	Always at CVS
3025A	3	Alternate
3772	11	Alternate
3772_CS	11	Always at CS
3776	2.5	Alternate
3790_PMP	23	Always at PMP

Results

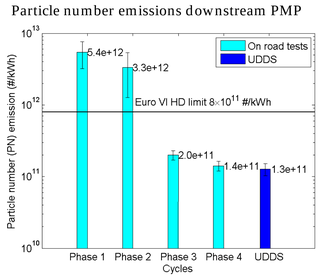
Comparison of on-road and Urban Dynamometer Driving Schedule (UDDS) tests

Phase 1 and 2 of the on-road test were uphill driving with positive road grades, while phase 3 and 4 were downhill driving. The on road test covers wide range of engine loads.

The engine load of the UDDS is similar to that of the phase 3 of the on-road test. And it is about 2 times of that of the phase 4 of the on-road test.



Particle number emissions downstream PMP



The UDDS particle number (PN) emissions are comparable to the phase 4 of the on-road test.

The UDDS particle mass (PM) emission are 2 times higher than the phase 3 and 4 of the on-road test.

The Euro VI heavy-duty PN limit is higher than the UDDS, phase 3, and phase 4 PN emissions.

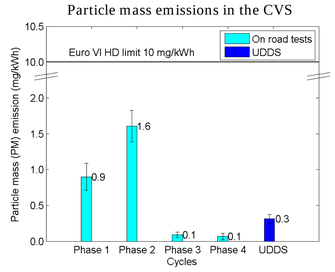
The Euro VI heavy-duty PM limit is higher than all 4 phases of the on-road test and the UDDS PM emissions.

PM emissions were calculated from the EEPS particle size distributions using the Integrated Particle Size Distribution (IPSD) method [4]. The effective density correlation was adopted from Maricq and Xu [5].

$$M_{IPSD} = \sum_i \rho_{eff,i} \times \left(\frac{4}{3}\pi \times \left(\frac{D_{p,i}}{2}\right)^3\right) \times n_i \times \Delta \log D_p$$

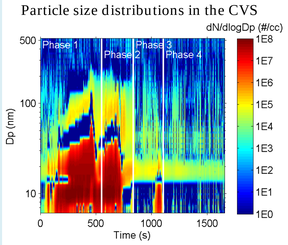
$$\rho_{eff,i} = \rho_0 \times \left(\frac{D_{p,i}}{D_{p0e}}\right)^{d_f - 3}$$

Particle mass emissions in the CVS



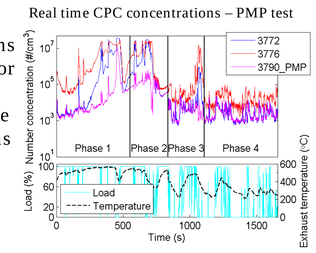
Comparison of PMP and CS to remove volatile particles under on-road conditions

Particle size distributions in the CVS



Particle size distributions in the CVS are similar for both the PMP and CS tests. Phase 1 and 2 have very high concentrations of both nucleation and accumulation mode particles.

Real time CPC concentrations – PMP test

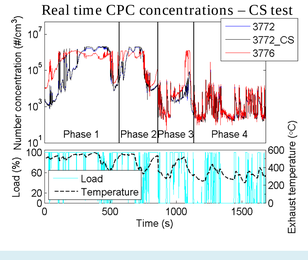


For the PMP test, the CPC 3776 has higher concentration than the CPC 3772 and 3790_PMP, suggesting the presence of re-nucleated sub 11 nm particles downstream the PMP system.

The discrepancy of the CPC 3772 and 3790_PMP at the end of phase 1 and beginning of phase 2 suggests the re-nucleated particles downstream of PMP can grow bigger than 11 nm.

For the CS test, the CPC 3776, 3772, and 3772_CS generally agreed well, indicating less tendency of forming of sub 11 nm particles than the PMP.

Real time CPC concentrations – CS test



Conclusions

- The particle number emission of the UDDS is comparable to the real-world driving with the lowest engine load, while the particle mass emission of the UDDS is 2 times higher than the lowest engine load on-road condition;
- The Euro VI heavy-duty particle number limit is lower than those on-road tests with average engine loads above 70% and higher than those on-road tests with average engine loads below 40%;
- The Euro VI heavy-duty particle mass limit is higher than the particle mass emissions of all on-road tests;
- The CS showed less tendency of forming sub 11 nm particles than the PMP system;
- During certain real-world driving conditions, the re-nucleated particles downstream the PMP system can grow larger than 11 nm.

References

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